Energy Conversion and Management 176 (2018) 334–348

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Numerical investigation of dual-fuel injection timing on air-fuel mixing and combustion process in a novel natural gas-diesel rotary engine

Wei Chen, Jianfeng Pan*, Baowei Fan, Peter Otchere, Nannan Miao, Yao Lu

School of Energy and Power Engineering, Jiangsu University, Zhenjiang 212013, Jiangsu, China

ARTICLE INFO

Keywords:
Natural gas
Diesel rotary engine
Dual fuel engine
Injection timing
Mixture formation
Combustion process

ABSTRACT

This study aimed at further improving the combustion efficiency of the diesel rotary engine (DRE), and in this regard a novel natural gas-diesel rotary engine (NG-DRE) was numerically studied. Based on the experimental validated computational fluid dynamics (CFD) model, a 3D-dynamic numerical study of the NG-DRE was carried out by adopting NG port injection plus diesel direct injection mode. The influence of natural gas injection timing (NGIT) and diesel injection timing (DIT) on air-fuel mixing, combustion and emission characteristics were explored. Simulation results showed that NG-DRE performance was better than DRE. During the entire air-fuel mixing process, NG movement was easily affected by the vorticity density due to its good diffusion characteristics, however its influence on diesel movement was relatively minimal. At assisted ignition timing, NG concentrated at the rear of the combustion chamber, and diesel concentrated at the front and middle of the combustion chamber. Delaying NGIT and DIT, the mixture became more concentrated due to a shorter mixing time. Moreover, the delayed NGIT and DIT resulted in improvement of the pressure and combustion rate, while for a further delayed DIT the pressure was decreased due to the pressure negative work. Considering the engine power and emission performance, for dual-fuel injection schemes, 340°CA BTDC and 70°CA BTDC were the preferred application schemes for NG and diesel respectively. Their peak combustion pressure (P_{max}) increased by 16.34% and 27.38% respectively, but due to the richer mixture, soot value increased by 0.023% and 0.054% and CO (carbon monoxide) value also increased by 0.026% and 0.039% respectively.

1. Introduction

The rotary engine (RE) is a kind of rotary-type internal combustion engine, having simple structure, high power-to-weight ratio [1], low noise and low vibration, high speed and wide range of fuel adaptability [2]. These advantages make it applicable in microelectromechanical systems (MEMS) [3] and compressed air energy storage (CAES) [4]. Especially due to its high power density [5], it has been widely used in unmanned aerial vehicle (UAV) [6]. Nevertheless, the rapid development of RE requires further expanding its applications fields. Recently, engineers and scholars have used RE as the power source for range extender by taking full advantage of its small engine size, lightweight and high power density characteristics. AVL List GmbH developed a range extender unit which had the power provided by RE [7]. Antonelli et al. and [8] Ribau et al. [9] did some meaningful experimental research on RE extender. Varnhagen et al. [10] numerically investigated the efficiency of range extending systems. Judgmentally, they all gave a positive evaluation on the RE range extender. These successful applications show that RE has a clear application prospects in the field of extended range power generation, and many automobile companies are actively developing this technology by using RE as the power source. Presently, under the trend of high efficiency, energy saving and low emissions demands of the internal combustion engine, the RE based on the traditional technology is facing the problem of low combustion efficiency and poor emission. Therefore, in order to meet the current market demand, it is urgent to develop new technologies suitable for RE to improve its performance. Thereby, many scholars have proposed new technologies to improve the RE combustion and emission characteristics. Amrouche et al. [2,11,12] used gasoline blending hydrogen and ethanol blending hydrogen techniques, Ji et al. [13] and Yang et al. [14] adopted gasoline blending hydrogen technology, Su and Ji et al. [15,16] chose butanol blending hydrogen technology, Fan and Pan et al. [17] adopted natural gas (NG) blending hydrogen technology. Zambalov et al. [18] used hydrogen plus with laser ignition system technology. These studies showed that using or blending gaseous fuel could effectively improve the combustion efficiency and emission performance of RE. At the same time, using dual-fuel technology, especially blending gaseous fuel was a reliable new technology for RE

* Corresponding author at: School of Energy and Power Engineering, Jiangsu University, 301 Xuefu Road, Zhenjiang 212013, China.
E-mail address: mike@ujs.edu.cn (J. Pan).

https://doi.org/10.1016/j.enconman.2018.09.050
Received 26 June 2018; Received in revised form 21 August 2018; Accepted 15 September 2018

Nomenclature

RE	rotary engine
CAES	compressed air energy storage
NG	natural gas
DIT	diesel injection timing
NG-DRE	natural gas-diesel rotary engine
NGIT	natural gas injection timing
NO_x	nitrogen oxides
HC	unburned hydrocarbons
ϕ_1	natural gas injection angle
λ	specific equivalence ratio
BTDC	before top dead center
UDF	user defined function
EDC	Eddy-dissipation concept
DPM	discrete phase model
P_{max}	peak combustion pressure
T_{max}	maximum combustion temperature
HO_2	hydroperoxyl radical
MEMS	microelectromechanical systems
UAV	unmanned aerial vehicle
DRE	diesel rotary engine
CFD	computational fluid dynamics
TDC	top dead center
NG-DPE	natural gas-diesel piston engine
CO	carbon monoxide
NO	nitric oxide
ϕ_2	diesel injection angle
η	natural gas blending ratio
ATDC	after top dead center
PIV	particle image velocimetry
KH-RT	Kelvin-Helmholtz and Rayleigh-Taylor
ERC	engine research center
MFB	mass fraction burned
φ_{max}	crank angle for peak combustion pressure
CO_2	carbon dioxide

improvement. However, these new technologies all focused on using the fuels of hydrogen-gasoline, hydrogen-NG, hydrogen-butanol and hydrogen-ethanol, without involving diesel blending gaseous fuel. In addition, if the fuel supply mode was only premix or port injection, the incomplete combustion problem in the rear of the combustion chamber cannot be solved fundamentally due to the forward flame propagation law.

Fortunately, the diesel rotary engine (DRE) can effectively solve the above mentioned incomplete combustion problem, since it operates with direct injection and stratified combustion [19]. Meanwhile, the DRE also has the advantages of power output, safety, fuel economy and thermal efficiency [20]. By using direct injection technology the fuel injection parameters can be flexibly controlled to properly organize the mixture distribution in the combustion chamber. Currently, the latest work carried out by Fan et al. [21] and Yang et al. [22] also show that the direct injection technology is the most effective way to solve the incomplete combustion problem of RE. Hence, the injection parameters are crucial for DRE. For several decades, scholars have been optimizing its injection strategy, especially the diesel injection timing (DIT) to improve the DRE performance, thus promoting its development and application. As for the experimental study, Wu et al. [19] studied DRE performance under different DITs, and the results showed that appropriately advanced fuel injection timing could increase the pressure. Morita et al. [23] studied the DRE air-fuel mixing process in the combustion chamber under different DITs. The results showed that the delayed DIT made the fuel to directly impact on the rotor wall and reduced the air-fuel mixing speed. In terms of numerical simulation, Abraham et al. [24,25] firstly established a 3D simulation model of DRE by using computational fluid dynamics (CFD) method. With the further development of CFD technology, it has been widely used and applied in engine research. Therefore, Izweik [26] studied the DIT effect on the air and fuel mixing process of DRE, and the results showed that the advanced DIT was conducive to the air and fuel mixing uniformly. Wadumesthrige et al. [27] and Votaw [28] also researched the air-fuel mixing and combustion process by changing the DITs, and the results showed that the advanced DIT was beneficial to the formation of homogeneous mixture. These meaningful studies provided basic data for the DRE development, at the same time they also showed that the DIT is vital to the mixture formation and combustion process of DRE. However, they all aimed at the single-fuel DRE, but were not concerned with the dual-fuel DRE, especially the natural gas-diesel rotary engine (NG-DRE).

As known, as a clean gaseous fuel, NG is a widely used alternative fuel for diesel engine. Due to its good diffusion characteristics, it can effectively solve the flame quenching problem which result from the large surface area/volume ratio and long and narrow combustion chamber near the top dead center (TDC) of RE. This is because NG can be timely and reliably ignited by the assisted ignition sources at assisted ignition timing, which is beneficial to accelerate flame propagation speed in the burning zone. At the same time, diesel blending NG can

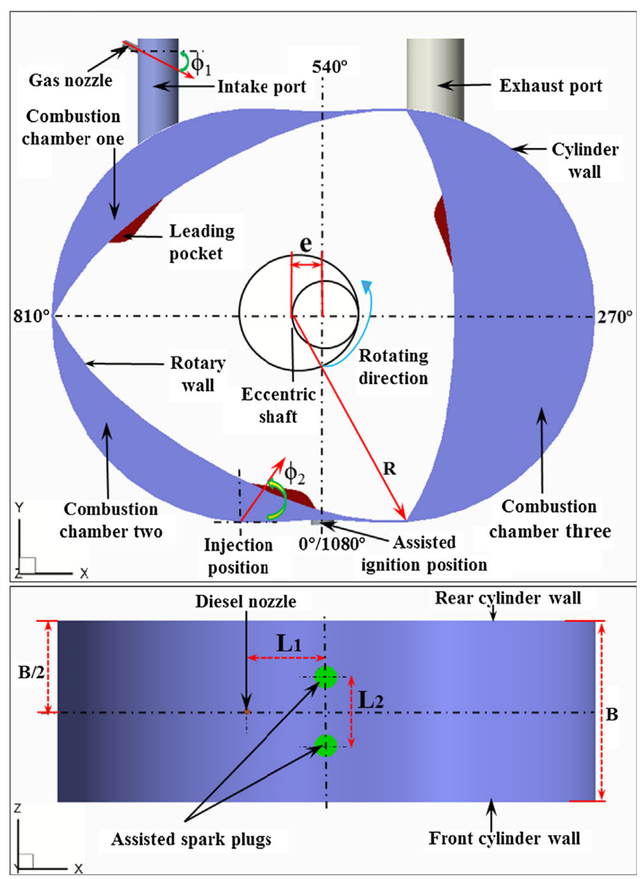

Fig. 1. 3D model of natural gas-diesel rotary engine.